A Hitchhikers Guide to the Black Arts
(of Earth system modelling)

III: Ocean circulation and overturning stability in cGENIE

Stuff to keep in mind:

- Nothing at all – keep your mind completely empty and let the wonderful truths of the GENIE-1 model permeate your entire being.

Relevant reading (and references therein):

Atlantic circulation and stability in GENIE:

Hargreaves et al. [2004] (Climate Dynamics, Volume 23, Issue 7 - 8, Dec 2004, Pages 745 – 760)
→ Simple assessment of the likelihood of AMOC collapse.

Marsh et al. [2004] (Climate Dynamics, Volume 23, Issue 7 - 8, Dec 2004, Pages 761 – 777)
→ Characterization of thresholds of AMOC collapse.

Singaraye et al. [2008] (GRL 35, doi:10.1029/2008GL034074)
→ Role of changing ocean circulation in atmospheric radiocarbon variability during the Younger Dryas.

Chikamoto et al. [2008] (JGR 113, doi:10.1029/2007JG00066)
→ Deep-sea CaCO3 sediment and atmospheric CO2 response to AMOC shutdown.

Miscellaneous (model) Atlantic circulation and stability:

Rahmstorf et al. [2006] (In: Encyclopedia of Quaternary Sciences, Edited by S. A. Elias. Elsevier, Amsterdam)
→ Provides the background to the Atlantic Meridional Overturning Circulation and hypothesized hysteresis.

IPCC [2007] (e.g., Section 10.3.4)
→ Future predictions of AMOC strength.

Schmittner [2005] (Nature 434, 628– 633)
→ Impacts on marine ecosystems and carbon cycling.

Obata [2007] (J. Clim. 20, 5962–5976)
→ Climate-carbon cycle model response to freshwater discharge.

9. Geochemical forcing of *c*GENIE ("poking the climate beast" [*Wally Broecker*])

9.0 The ocean biogeochemistry module ('*BIOGEM*') in *c*GENIE provides a framework for applying time- and spatially-variable '*forcings*' of the Earth system – fluxes or restored-to boundary conditions that can be prescribed for any gas, dissolved substance, or particulate, and including temperature and salinity. Examples include freshwater input (== a negative salinity flux *forcing*) of the North Atlantic to alter ocean circulation, fossil fuel CO_2 emissions to the atmosphere (== a CO_2 gas flux *forcing*), or aeolian iron supply to the surface ocean (based on a 2-D detrital, dust flux forcing field).

9.1 Section 4 in the *User Manual* describes the original and most flexible provision for applying time-dependent *forcings*. However, a simpler :) way is provided of applying *forcings* in *c*GENIE compared to the gobbledygook in the *User Manual*, and geochemical fluxes (or boundary conditions) can be specified in just a few additional lines in the *user-config* file if the forcing has a simple spatial pattern (e.g., fluxes applied equally to the entire ocean, to the entire surface, or to a single location in the ocean).

For example: view the *user-config* file: `exp6_colorinjection`. You will see the following new lines (under the heading: '`# --- FORCINGS ---`')

```
#
# --- FORCINGS -------------------------------------------------------
#
bg_ctrl_force_oldformat=.false.
bg_par_forcing_name="pyyyyz_Fred"
bg_par_force_point_i=22
bg_par_force_point_j=33
bg_par_force_point_k=8
bg_par_ocn_force_scale_val_48=0.0
```

The first line simply tells *c*GENIE to ignore the complicated ('old') way of specifying forcings (Section 4 in the *User Manual)*. The second line points *c*GENIE to a set of files that define what geochemical property is going to be altered plus information about how the forcing changes with time (if at all). These two lines you do not need to worry about any further here.

There are three lines (`bg_par_force_point_i=20`, ...) that specify the location in the ocean of the geochemical forcing is going to be applied. The point sources are specified in (`i,j,k`) coordinates, which in this case is (`22,33,08`). For the ocean model resolution we are using, the grid is 36×36×16, longitude (`i`) is counted from left-to-right (1 to 36); latitude (`j`) is counted from bottom-to-top (1 to 36); level depth (`k`) is counted from downwards top-to-bottom (16 down to 1). Thus, (`22,33,08`) is a release of tracer in the North Atlantic, a little south of Greenland, and intermediate depth (level = 8 out of 16). Refer to the Figure for grid information.
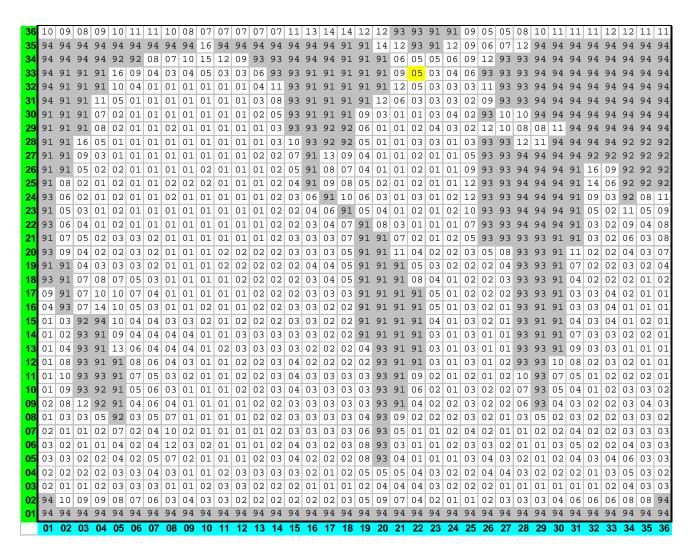
Finally, there is a scaling parameter (`bg_par_ocn_force_scale_val_48`) which specifies the magnitude of the flux to be applied (in units of mol yr^{-1}).

9.2 You are going to run a brief experiment in which you will be injecting a conservative dye tracer in the ocean. BIOGEM has two tracers defined for this purpose – 'blue' and 'red'. Open the *user-config* file: `exp6_colorinjection` and edit the parameter controlling the flux of red dye to read:

`bg_par_ocn_force_scale_val_48=1.0E12`

which specifies a flux of 1.0×10^{12} (mol yr^{-1}).

The experimental design is a different from the modern simulation used previously in e.g. Section 7, primarily in that a new *base-config* (`cgenie_eb_go_gs_ac_bg.worjh2.rb`) is being used here – this specifies a higher resolution ocean model with 16 levels in the vertical. Also now included is seasonality of solar insolation. (Note that you will need to carry out a `make cleanall` because *c*GENIE was last configured in a snowball Earth configuration).

```
36│ 10 09 08 09 10 11 11 10 08 07 07 07 07 07 11 13 14 14 12 12 93 93 91 91 09 05 05 08 10 11 11 11 12 12 11 11
35│ 94 94 94 94 94 94 94 94 94 16 94 94 94 94 94 94 94 91 91 14 12 93 91 12 09 06 07 12 94 94 94 94 94 94 94 94
34│ 94 94 94 94 92 92 08 07 10 15 12 09 93 93 94 94 94 91 91 91 06 05 05 06 09 12 93 93 94 94 94 94 94 94 94 94
33│ 94 91 91 91 16 09 04 03 04 05 03 03 06 93 93 91 91 91 91 91 09 05 03 04 06 93 93 93 94 94 94 94 94 94 94 94
32│ 94 91 91 91 10 04 01 01 01 01 01 01 04 11 93 91 91 91 91 91 12 05 03 03 03 11 93 93 94 94 94 94 94 94 94 94
31│ 94 91 91 11 05 01 01 01 01 01 01 01 03 08 93 91 91 91 91 12 06 03 03 03 02 09 93 93 94 94 94 94 94 94 94 94
30│ 91 91 91 07 02 01 01 01 01 01 01 01 02 05 93 91 91 91 09 03 01 01 03 04 02 93 10 10 94 94 94 94 94 94 94 94
29│ 91 91 91 08 02 01 01 02 01 01 01 01 01 03 93 93 92 92 06 01 01 02 04 03 02 12 10 08 08 11 94 94 94 94 94 94
28│ 91 91 16 05 01 01 01 01 01 01 01 01 01 03 10 93 92 92 05 01 01 03 03 01 03 93 93 12 11 94 94 94 94 92 92 92
27│ 91 91 09 03 01 01 01 01 01 01 01 01 02 02 07 91 13 09 04 01 01 01 01 05 93 93 94 94 94 94 92 92 92 92 92 92
26│ 91 91 05 02 02 01 01 01 01 02 01 01 01 02 05 91 08 07 04 01 01 02 01 01 09 93 93 94 94 94 91 16 09 92 92 92
25│ 91 08 02 01 02 01 01 02 02 02 01 01 01 02 04 91 09 08 05 02 01 02 01 01 12 93 93 94 94 94 91 14 06 92 92 92
24│ 93 06 02 01 02 01 01 02 01 01 01 01 01 02 03 06 91 10 06 03 01 03 01 02 12 93 93 94 94 94 91 09 03 92 08 11
23│ 91 05 03 01 02 01 01 01 01 02 02 04 06 91 05 04 01 02 01 02 10 93 93 94 94 94 91 05 02 11 05 09
22│ 93 06 04 01 02 01 01 01 01 01 01 02 03 04 07 91 08 03 01 01 01 07 93 93 94 94 94 91 03 02 09 04 08
21│ 91 07 05 02 03 03 02 01 01 01 01 02 03 03 03 07 91 91 07 02 01 02 05 93 93 93 93 91 91 03 02 06 03 08
20│ 93 09 04 02 02 03 02 01 01 01 02 02 02 02 03 03 05 91 91 11 04 02 02 03 05 08 93 93 91 11 02 02 04 03 07
19│ 91 91 04 03 03 03 02 01 01 01 02 02 02 02 04 04 05 91 91 91 05 03 02 02 02 04 93 93 91 07 02 02 03 02 04
18│ 93 91 07 08 07 05 03 01 01 01 01 02 02 02 02 03 04 05 91 91 91 08 04 01 02 02 03 93 93 91 04 02 02 02 01 02
17│ 09 91 07 10 10 07 04 01 01 01 01 02 02 03 03 03 91 91 91 91 05 01 02 02 02 93 93 91 03 03 04 02 01 01
16│ 04 93 07 14 10 05 03 01 01 02 01 01 02 03 03 02 91 91 91 91 91 05 01 03 02 01 93 91 91 03 03 04 01 01 01
15│ 01 03 92 94 10 04 04 03 03 02 01 02 02 03 03 02 91 91 91 91 04 01 03 02 01 93 91 91 04 03 04 01 02 01
14│ 01 02 93 91 09 04 04 04 01 01 03 03 03 03 02 01 91 91 91 91 03 01 03 01 01 93 91 91 07 03 03 02 02 01
13│ 01 04 93 91 13 06 04 04 01 02 03 03 03 02 02 04 93 91 91 03 01 03 01 01 93 93 91 09 03 03 01 01 01
12│ 01 08 93 91 91 08 06 04 03 01 01 02 02 03 04 02 02 02 02 93 91 91 03 01 03 01 02 93 93 10 08 02 02 01 01
11│ 01 10 93 93 91 07 05 03 02 01 01 02 02 03 04 03 03 03 93 91 09 02 01 02 01 02 10 93 07 05 01 02 02 02 01
10│ 01 09 93 92 91 05 06 03 01 01 01 02 02 03 04 03 03 03 93 91 06 02 01 03 02 02 07 93 05 04 01 02 03 03 02
09│ 02 08 12 92 91 04 06 04 01 01 01 02 02 03 03 03 03 03 93 91 04 02 02 03 02 02 06 93 04 03 02 02 03 04 03
08│ 01 03 03 05 92 03 05 07 01 01 01 02 02 03 03 03 03 04 93 09 02 02 02 03 02 01 03 05 02 03 02 02 03 03 02
07│ 02 01 01 02 07 02 04 10 02 01 01 01 02 03 03 03 03 06 93 05 01 01 02 04 02 01 01 02 02 04 02 02 03 03 03
06│ 03 02 01 01 04 02 04 12 03 02 01 01 01 02 04 03 02 03 08 93 03 01 01 02 03 03 02 01 03 05 02 02 04 03 03
05│ 03 03 02 02 04 02 05 07 02 01 01 01 02 03 04 02 02 08 93 04 01 01 01 03 04 03 02 01 02 04 03 04 06 03 03
04│ 02 02 02 02 03 03 04 03 01 01 02 03 03 03 02 01 02 05 05 04 03 02 02 04 04 03 02 02 02 01 03 05 03 03
03│ 02 01 01 02 03 03 03 01 01 02 03 03 02 02 01 01 01 02 04 04 04 03 02 02 01 01 01 01 01 01 02 04 03 03
02│ 94 10 09 09 08 07 06 03 04 03 03 02 02 02 02 02 03 05 09 07 04 02 01 01 02 03 03 03 04 06 06 06 08 08 94
01│ 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94 94
    01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
```

***c*GENIE grid** (36×36 'worjh2' configuration)**.**
Light blue numbers are the '**i**' co-ordinates. Green numbers are the '**j**' co-ordinates.
The depth of the ocean at any location is indicated by its 'k' value – a number between 1 and 16, with 16 being the surface layer of the ocean, and 1 the maximum possible depth anywhere.
Numbers > 90 (91, 92, 93, 94) and shaded grey are land (and specify the direction of run-off).
Location (22,33,08) is highlighted in yellow.

Run the model for e.g. 20 or 50 years using a new (16-level ocean) pre-industrial spin-up that is provided as a restart:

```
$ ./runcgenie.sh cgenie_eb_go_gs_ac_bg.worjh2.rb LABS
  exp6_colorinjection 50 exp0_modern16_SPINUP
```

View the results – the impact on the Red tracer distributions in NetCDF time-slice files. For instance, the 2-D NetCDF file (fields_biogem_2d.nc) has fields of bottom-water properties which facilitate tracking the dispersal of tracers released at depth (e.g., variable: ocn_colr). Changes in tracer inventory with time can be tracked in the time-series file biogem_series_ocn_colr.res.

Spend a little while altering the flux (bg_par_ocn_force_scale_val_48) and/or location (bg_par_force_point_i, bg_par_force_point_j, bg_par_force_point_k) of tracer input. Note how you can use conservative tracers to help diagnose (and better understand) the circulation of the ocean.

You can follow the progress of the dye (and hence diagnose the properties of ocean circulation in the model) by plotting vertical and/or horizontal slices that go through (or near) the cell location in which you inject the dye tracer (3D netCDF file). You can also plot the overturning circulation from

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the 2D netCDF file – variable `phys_opsi` == global overturning streamfunction, `phys_opsia` == overturning in the Atlantic.

The progress of the dye plume can also be easily followed in the BIOGEM 2D netCDF file by viewing the water-column integrated tracer inventory variable (netCDF variable name: `ocn_int_colr`; long name: `colr water-column integrated tracer inventory`). See: *Sabine et al.* [2004] for the use of water column integrals (in this case, in the context of the distribution of anthropogenic CO_2 uptake and storage).

9.3 You can also select an additional, 'blue' dye *tracer*. To do this, you will need to edit the file: `configure_forcings_ocn.dat`, which can be found in the `cgenie/genie-forcings/pyyyyz_Fred` directory. This directory contains the basic specification of the *forcing*, such as which *tracer* is going to be adjusted ('forced'), whether the *forcing* should be *restoring* (to a prescribed value) or a *flux*, etc (see: *User Manual*).

To start with – it is probably best if you create a new forcing specification for both tracers, by copying and renaming the `pyyyyz_Fred` directory (e.g., to `pyyyyz_Fredblue`). (See the linux tips in Appendix I and/or Google your way out of jail.) In: `configure_forcings_ocn.dat` you need to create a new line under the existing one:

```
48   F   T   1.0   T   F    0   21   03   08    '[RED numerical (color) tracer (n/a)]'
```

The new line can be identical, except for a '`49`' in the first 'column' (`01`). For completeness, note that the additional tracer being forced is the `BLUE` one in the last, comment column …

You will also have to create a file specifying the time-dependent information for the forcing in the directory. For the red tracer, this file is already present and called:

`biogem_force_flux_ocn_colr_sig.dat`

Copy this file and rename to:

`biogem_force_flux_ocn_colb_sig.dat`

The '`colb`' bit is a mnemonic for the blue color tracer. (The mnemonics (and index numbers) for the various tracers in GENIE are listed in the *cgenie.namelists* document.)

Finally, you need to add the line to the user config file a flux scaling, e.g.:

`bg_par_ocn_force_scale_val_49=1.0E12`

k	mid depth (m)	base of layer (m)
16.00	38.91	80.84
15.00	126.04	174.75
14.00	227.26	283.85
13.00	344.84	410.58
12.00	481.44	557.80
11.00	640.12	728.83
10.00	824.45	927.51
9.00	1038.59	1158.31
8.00	1287.35	1426.43
7.00	1576.33	1737.90
6.00	1912.04	2099.73
5.00	2302.02	2520.05
4.00	2755.05	3008.34
3.00	3281.33	3575.57
2.00	3892.71	4234.52
1.00	4602.92	5000.00

GENIE-1 ocean vertical level definitions

(16-level configuration)

You have now added a new forcing of the model. It actually is not very exciting because the two tracers are being added in identical positions, set by the 3 parameters in the *user-config* file:

`bg_par_force_point_i=22`

`bg_par_force_point_j=33`

`bg_par_force_point_k=8`

that over-write the locations set in the forcing itself. You can set independent locations for the red and blue dyes by editing the default (i,j,k) locations in `configure_forcings_ocn.dat` (columns: `07, 08, 09`) and then commenting out (#) 3 lines in the *user-config* file.

(The full and most flexible way of configuring and applying *forcings* is detailed in the *user manual.*)

9.4   An interesting (honest!) and illustrative exercise is too use the dye tracer (either one) to pick out the path taken by Mediterranean Intermediate Water. Despite the low resolution of the *c*GENIE ocean circulation model component and the highly restricted representation of the Mediterranean, the model does predict a salty Mediterranean as a consequence of P-E in this basin (and its catchments) being negative and this water makes its way out in the subsurface into the Atlantic.

Simply specify a dye injection somewhere in the Mediterranean (be careful with the restricted depth of the Mediterranean – if you inject too deeply (into the crust!) then you will not see anything (refer to the figure for the depth level (`k`) number of the maximum depth of the water column in each location), and it is better to inject it <u>relatively close</u> to the opening of the gateway (try some different locations and see which ones produce a reasonably instructive tracing of Mediterranean outflow). Run for e.g. 20 or 50 years (from the provided *spin-up*). Then:

(1) View the dye-tagged plume of Mediterranean Intermediate Water by plotting a `lat-lon` slice (from the 3D netCDF file). This will give you the depth of the plume. How does this compare with salinity observations (salinity observations and appropriate global datasets can be found on the web with a little patience)? You can also view the water-column integrated distribution (2D netCDF).

(2) Try viewing the plume via a `lat-depth` slice. Refer to the figure to determine the 'i' value up the Atlantic that will just graze the edge of what passes for Spain at this low model resolution. Which direction does it head after exiting the Mediterranean? Is this 'realistic'?

9.5   Instead of adding a dye tracer, you could add fresh water to assess the sensitivity of the Atlantic Meridional Overturning Circulation (AMOC) to collapse. You will be carrying a classic 'hosing' experiment (i.e., in the model, as if you were directing a garden hose of tap-water at the North Atlantic) and running a series of model experiments with differing fluxes of freshwater into the ocean.

The new *user-config* file is called: `exp7_hosing`. The default (`i,j`) location of the flux input is the same, but now the injection is to the surface (level: `k=16`) of the ocean. Note that the forcing of the salinity tracer is negative (freshwater = negative salinity compared to sea-water)! (See below for some exciting units discussion!) To orientate you in freshwater forcing space: `bg_par_ocn_force_scale_val_2=-2.0E17` should be sufficient to make 'stuff happen' and quickly. **BUT**, this is a pretty extreme flux (see overleaf for a rough conversion between salinity forcing units (mol yr-1) and fresh water flux (in $m^3 s^{-1}$ or Sv). Much more than this and the model may crash or at the very least, you'll be left with a large freshwater pond in the North Atlantic …

To run the model for e.g. 20 years using the same re-start:

```
$ ./runcgenie.sh cgenie_eb_go_gs_ac_bg.worjh2.rb LABS exp7_hosing 20 exp0_modern16_SPINUP
```

20 years should be long enough to see a collapse start to occur, but you might want to run the model for longer, e.g., 50 or 100 years. (Running it longer will also allow you to have a smaller, less extreme freshwater input flux and still see anything happen.)

The most obvious property of the Earth system to follow is the Atlantic overturning strength (`biogem_series_misc_opsi.res`). The AMOC stream-function (in `fields_biogem_2d.nc` 2-D time-slice netCDF results file, field: `phys_opsia`) is also illustrative. You can also try and identify the salinity **anomaly** (see below) due to freshwater input in the 3D salinity tracer field.

There are also important impacts on surface air temperatures (field: `atm_temp` in `fields_biogem_2d.nc`). Note the importance of the AMOC in transporting heat to NE American and NW Europe (the file the Day After Tomorrow was not entirely inaccurate in this particular respect). Be aware of the possibility of climate impacts far from the location of fresh water forcing. Look out for any significant-looking impacts on sea-ice extent, etc. Equally, you could plot the ocean surface temperature (field: `ocn_sur_temp` in `fields_biogem_2d.nc`).

(<u>See overleaf for hints on plotting!</u>)

QUESTIONS: What is the largest freshwater flux that can be sustained without 'collapsing' the AMOC (say, to below 5 or 1 Sv strength)? Is there a 'threshold' ('tipping point') of freshwater input, beyond which the AMOC rapidly decreases in strength? How important is the precise location of the freshwater input (i.e., try tipping it in somewhere else)? What would you expect to see in the paleo (e.g., ice core) record of both hemispheres if such a shutdown occurred in the past?

9.5a To more easily assess some of these impacts (and for other sorts of analysis), it is possible to create an **anomaly** (difference) map in Panoply:

1. First open a dataset, e.g., `atm_temp` (surface air temperature) in the 2D netCDF file.

2. From the upper LH corner of the Dataset Browser window, from the drop-down menu, select the name of the plot you have just created (`atm_temp` in `field_biogem_2D` ...).

3. Again from the upper LH corner of the `Dataset Browser` window, now click on the `Combine Plot` icon.

4. You now have a plot window that is displaying a difference map. By default, it is showing you the difference between two identical (in time) slices. The two different slices are labeled `Array 1` (LH side) and `Array 2` (RH side).

Keep one array (`Array 1`) fixed to the initial (year 1 (centered on 0.5)) and vary the year in the second array (`Array 2`). Note that you can select in Panoply whether `Array 1 – Array 2` is plotted, or `Array 2 – Array 1`, or various proportional or relative differences.

Note that you can switch off the auto-scaling feature (`Always fit to data`) and center the scale so that no change is white, with positive deviations = red and negative = blue by clicking on `Center on 0`.

You can also plot ocean current fields which is sort-of fun and maybe even informative(!):

1. Open 2D netCDF file. The three components of ocean velocity are represented by the variables: `ocean velocity – u` (Eastwards velocity), `ocean velocity – v` (Northwards), and `ocean velocity – w` (upwards velocity).

2. Open up `velocity – u`. Chose 'lon-lat'.

3. Switch from '<new plot window>' to 'phys_u in fields_biogem_3D' in the Datasets Browser window (upper LH corner) as per creating a difference map (see above).

4. Open up `velocity – v`.

4. Rather than a difference map, which is what you get by default, i.e. 'Array 1 – Array 2' – from the drop-down menu (next to the 'Interpolate' button) select 'Vector Magnitude'.

5. You should have a color contoured (or not if you prefer plotting without contouring on) map of ocean current speed, with velocity vectors (direction and magnitude) overlain. You'll need to re-scale the velocity vectors to properly see them – from the 'Contours and Vectors' tab – change the 'Scale Length' to e.g. 0.1. When fresh-water hosing – look out for impacts on the N. Atlantic current system associated with the AMOC.

6. You can repeat this for deeper depth levels in the ocean – e.g. between about 1500 and 2000 m is a good place to go looking for the Western boundary current (and AMOC return) in the model (such as it exists at this low resolution) but you'll need to re-scale the velocity vectors again (e.g. to 0.01 to less).

9.5b A brief note on units ... the freshwater forcing is implemented as negative salinity, just to really screw with your mind. The units are PSU yr^{-1}. Which sort of does not mean much to me either ...

A value of `bg_par_ocn_force_scale_val_2` of -34.9 would be equivalent to taking all the salt out of 1 kg of freshwater since the mean global salinity is 34.9 PSU. Or equivalently, since the ocean volume is fixed (the ocean model uses the 'rigid lid' approximation/assumption), -34.9 is equivalent to adding 1 kg of freshwater to a (surface) box. So, a value of `bg_par_ocn_force_scale_val_2` of -3.49×10^4 (-3.49E04) would be a flux of 1 m^3 yr^{-1} (1000 kg m^{-3}) of freshwater.

So, in the example above (`bg_par_ocn_force_scale_val_2=-1.0E18`), the freshwater flux is 1.0×10^{18}/3.49×10^4 = 2.8653×10^{13} m^3 yr^{-1}.

The literature invariably gives freshwater fluxes in units of Sv (10^6 m^3 s^{-1}). So in the example, the freshwater flux is: 9.0797×10^5 m^3 s^{-1} (365.25×24×3600 = 31557600 s yr^{-1}). Or 0.9 Sv. Read the literature … but generally, fluxes of not much less than 0.05 Sv (and to quite specific places) have to be applied in models in order to induce a collapse of the AMOC.